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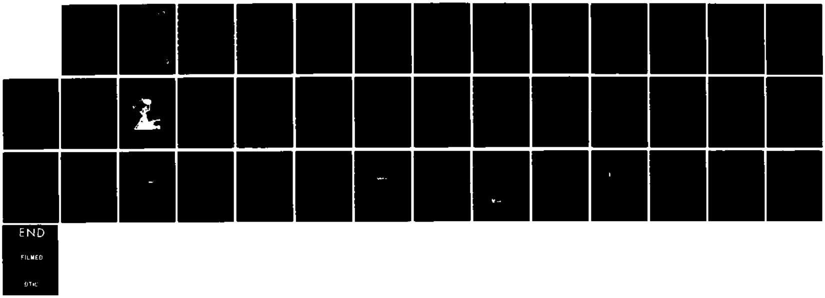

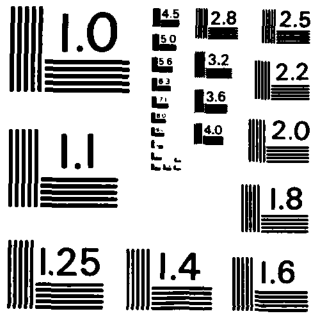

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FINAL REPORT
AFOSR GRANT 82-0206

STUDY OF THE EFFECTS OF TRIGGERED LIGHTNING

Prepared by

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ABSTRACT

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The development of an 11 cm radar was completed for a determination of the interaction between lightning and the surrounding atmosphere. Preliminary data on lightning echoes have now been obtained with it.

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INTRODUCTION

Natural lightning produces a number of interesting effects that are not understood because of the difficulty of studying these short lived discharges that occur at unpredictable times and at random locations. The damage that lightning causes to many human artifacts is difficult to assess because of the scarcity of direct strikes to a given point. For similar reasons, it is difficult to measure directly the electrical currents in a lightning channel and to study the waveforms associated with the electrical breakdowns leading to a discharge.

It is often noted that intense rain often falls from a thundercloud two or three minutes after a lightning discharge in that part of the cloud. Some investigators have suggested that this lightning was caused by cloud electrification arising from the fall of already charged precipitation within the cloud and the lightning then propagated more rapidly than the rain and thus was seen first. Some radar studies of thunderclouds (Moore et al., 1962; Szymanski et al., 1980) however, have indicated on occasion, that the intense rains falling after nearby lightning were not even present in the cloud before the discharge: Rapidly intensifying precipitation echoes to a scanning radar have been first detected 0.6 sec. or so after overhead lightning. These echoes then intensified at rates in excess of 30 dB/min and propagated toward the earth producing a transient burst of rain that arrived two or three minutes after the discharge.

Since the maximum rate at which precipitation echoes to radar can intensify as a result of gravitationally-induced collisions between cloud droplets of differing sizes is about 11 dB/min (Moore and Vonnegut, 1974) these observations indicate that the rain echoes following lightning are intensifying about 100 fold that possible under gravitational forces alone and that the mean volumes of the growing rain droplets are increasing at a rate of about 10 fold greater than the gravitational rate.

These observations thus suggest that lightning discharges may aid in the sudden formation of precipitation in clouds and therefore lightning thus may be responsible for much of the rains that fall from thunderclouds with intensities greatly in excess of the rates to be expected from the Wegener-Bergeron process. These radar findings are sparse, however, and this is probably because radars scanning the whole sky with narrow beams have low probabilities of intercepting the source region of a randomly occurring, localized lightning discharge at the critical time.

Lightning could be studied much better if it could be induced to occur in front of a battery of measuring instruments at a predetermined time. For this reason, there have been numerous attempts to initiate lightning artificially. Newman (1958) proposed to 'precipitate' lightning by projecting a 300 m long wire toward thunderclouds and thereby intercept natural lightning discharges. Brook et al. (1961) found that spark discharges could be artificially initiated by the rapid injection of a grounded conduction into regions with strong electric fields beneath the high voltage electrode of the 5 MV Van de Graaff generator at the Museum of Science in Boston.

Newman and his associates first demonstrated (in 1962) the controlled triggering of lightning by use of small rockets towing grounded wires toward thunderclouds over water from a ship off the east coast of Florida. Attempts to trigger lightning over the land were generally unsuccessful for the next few years and this was attributed to the fact that strength of the electric fields over land is generally weaker than over water as a result of point discharge from exposed, curved conductors.

A number of rocket development programs were instituted in this period by NASA and by Defense Department agencies but none of them were notably successful in triggering lightning nor in deploying wires at the speeds required by the rapidly accelerating rockets that were used.

Pierre Hubert and his associates in the French Commissariat a l'Energie Atomique (Saclay) developed successful wire dispensing techniques in the early 1970's then used a small, antihail, cloud-seeding rocket for lightning triggering experiments. This rocket deployed wires adequately without causing wire breakage. As one result of the French effort, it is now possible to trigger lightning reliably over land with a small rocket towing a grounded wire upward whenever a net negative charge is overhead and the electric field strength at the surface of the earth is in excess of 9 kV/m. A rapidly moving, wire-trailing rocket, launched under these conditions, produces an upward-going, positive streamer when the rocket reaches a height of the order of 200 m above the local terrain.

To cause a lightning streamer beneath a thundercloud, it appears necessary that the rocket move through the air faster than do the positive ions that are emitted from the upper end of the wire. Otherwise, an accumulation of these ions reduce the local electric fields below the strength needed for production of a streamer. The estimated drift velocities of positive ions in the electric fields at a height of 200 m are of the order of 100 m/s. Thus, positive ions are not accumulated above the French rocket which has an upward velocity in excess of 150 m/s at the altitudes of interest.

THE 1982 EXPERIMENT

Plans

As a result of a successful, rocket firing and lightning triggering program at Langmuir Laboratory (in the mountains of central New Mexico) during the summer of 1981 by collaborating investigators from France and from the United States, a more detailed study was carried out in New Mexico during the 1982 thunderstorm season. In the period between July 8 and August 19, 1982, Dr. Pierre Hubert and his associates (MM. Pierre LaRoche, Andre Eybert Berard, Louis Barret, Philip Richard, and others) performed various triggering experiments and made interferometric measurements extending their earlier work.

Richard Richmond of the Flight Hazards Branch, Air Force Wright Aeronautical Laboratories, Wright Patterson Air Force Base,

instrumented a simulated aircraft fuselage that was suspended from an 18 m high tripod to measure the resulting electromagnetic disturbances within the test shape whenever the device was struck by triggered lightning. This was part of a study of the effects of lightning on later generation computer-controlled air planes.

The New Mexico Tech effort, under support from the Air Force Office of Scientific Research, was aimed at continuing and extending the study of triggered lightning discharges by:

1. direct measurements of the lightning currents to earth,
2. by participating in the Wright Patterson AFWAL/FIESL experiment with simulated aircraft shapes,
3. by investigating the nature of lightning echoes to radar and,
4. by determining the effect of these discharges on the thunderclouds under various conditions of storm development and rain shaft locations.

We also wished to investigate our own means of triggering lightning by use of smaller rockets from South Baldy Peak (a map of the area is shown in Figure 1).

Lightning Triggerings

The 1982 summer thunderstorm season was moderately successful in meeting some of these goals. In the period between July 29 and August 21, 1982, a total of 31 rockets were launched beneath thunderclouds and lightning was triggered as a result on 17 occasions. Eight of these rockets were fired by the French in the development of an experimental technique aimed at initiating lightning discharges aloft without the use of a grounded wire; none of these special rockets initiated a lightning discharge. Three of the successful triggerings were carried out by New Mexico Tech personnel; two of these were with Ruggerei rockets while one triggering was caused by a small American rocket.

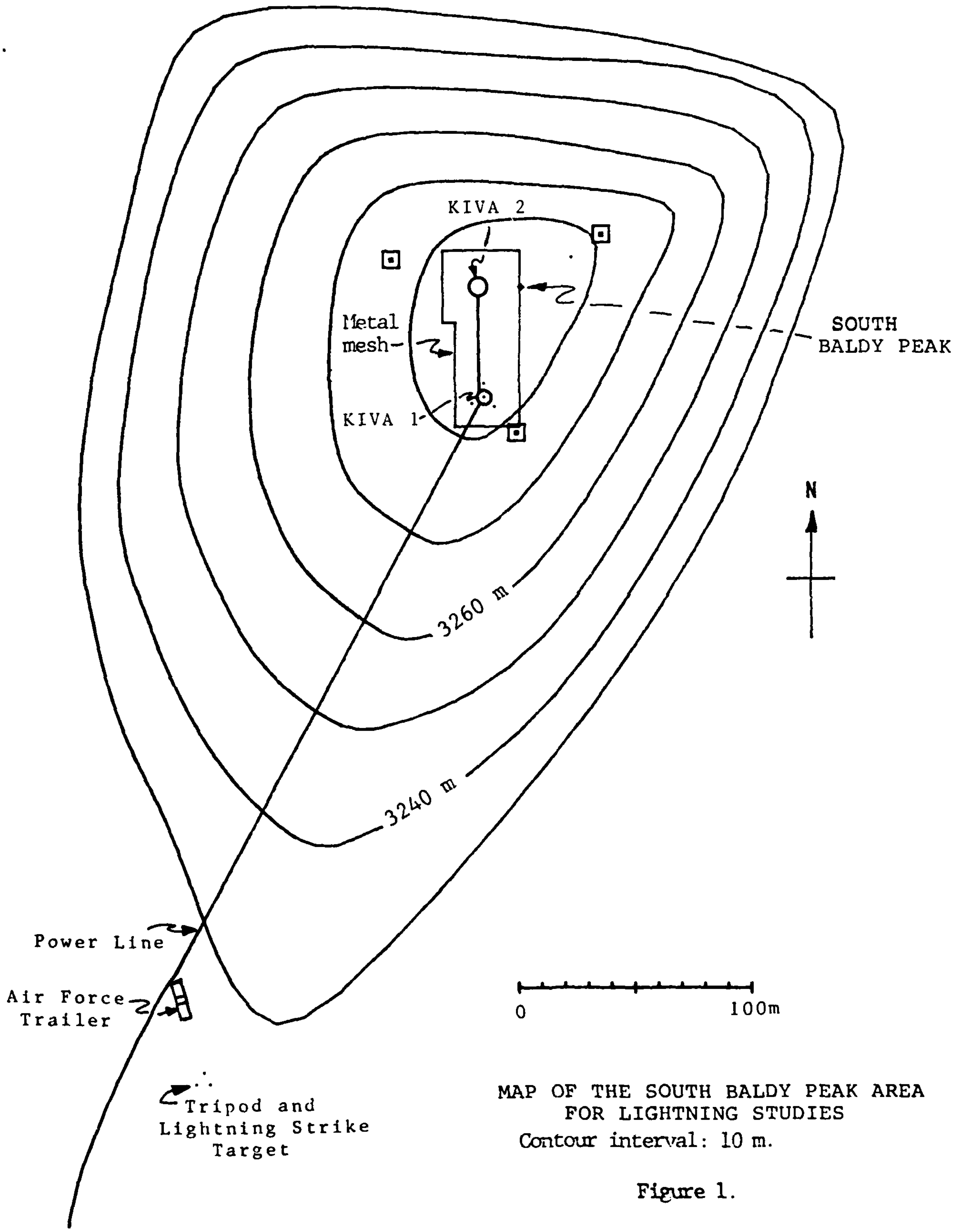
Data on these launches are listed in Table 1. No means for tracking any of these rockets were available so that their performance is unknown. The need for information on rocket trajectories led to the studies described in Appendix 1.

Three of the 14 discharges triggered by the French group struck the Air Force test object. The dates and times for these discharges are listed in Table 2 and a photograph of the discharge is shown in Figure 2.

All of these triggered flashes occurred when negatively charged cloud bases were over the launch sites. The strength of the electric fields at the surface of the earth just before the triggered flashes--ranged from 6.6 kV/m to 19 kV/m. In each case lightning was initiated when a upward-going, positive streamer propagated upward from the top of a wire being raised by a rocket. The lowest height at which lightning was triggered was about 112 m when a rocket was launched from the summit of South Baldy under electric field strengths of 19 kV/m.

Instrumentation

Measurements of the characteristics of triggered lightning were made and recorded at four different locations around the



MAP OF THE SOUTH BALDY PEAK AREA
FOR LIGHTNING STUDIES
Contour interval: 10 m.

Figure 1.

TABLE 1

LIST OF 1982 ROCKET LAUNCHES

French Rocket Launches from the Tripod at Base of South Baldy

Launch Number	Year/Julian Date	1982 Date	MST	Rocket Configuration	Triggered Lightning
8200	82207	July 26	1920	Tipsy (Note 1&2)	No
8201	82210	July 29	1320:55	Tipsy	No
8202			1322:46	GW (Grounded Wire)	Yes
8203			1324:48	Tipsy	No
8204	82212	July 31	1012:43	GW	Yes
8205			1015:41	Tipsy	No
8206			1018:24	Tipsy	No
8207			1024:21	GW	Yes
8208	82215	Aug. 3	1218:20	GW	No
8209			1230:17	GW	Yes
8210	82217	Aug. 5	1630:36	GW	Yes
8211			1632:03	GW	Yes
8212			1743:56	GW	Yes
8213	82219	Aug. 7	1151:35	GW	Yes
8214			1154:59	GW	Yes
8215			1156:23	Tipsy	No
8216			1202:30	GW	Yes
8217			1205:07	Tipsy	No
8218			1210:50	Tipsy	No
8219			1756:41	GW	Yes
8220	82224	Aug. 12	1614:44	GW	Yes
8221			1639:41	GW	No
8222	82228	Aug. 16	1730	GW	Yes
8223			1810	GW	No
8224			1815	GW	Yes

Wright-Patterson Air Force Rocket Launches from Tripod

1	82217	Aug. 5	1755:04	GW	No
2	82219	Aug. 7	1209:57	GW	No

KIVA Rocket Launches from South Baldy Peak

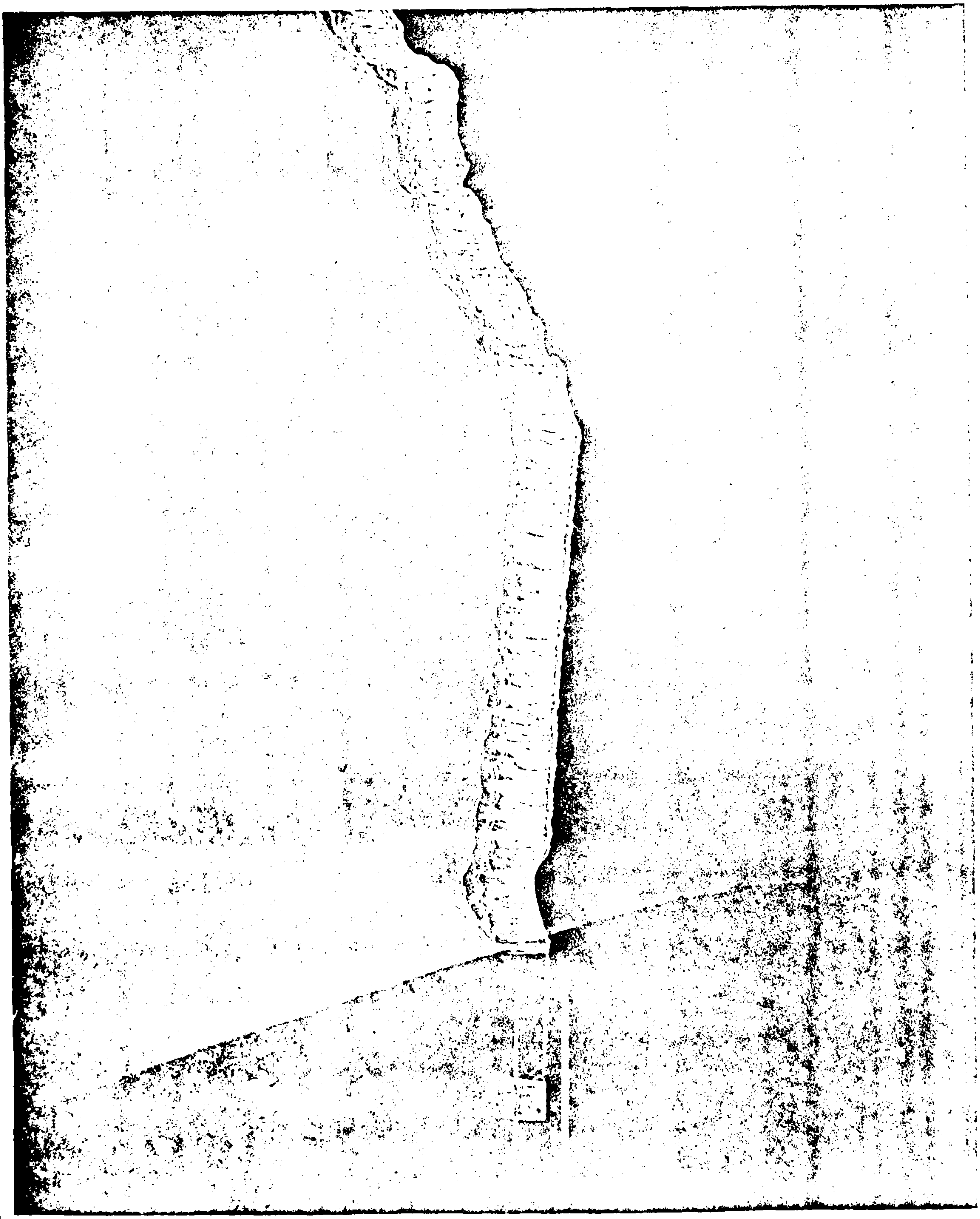
1	82217	Aug. 5	1748:15	Roos type with GW to Sandia Cable	No
2	82230	Aug. 18	1341:11	Ruggerei GW to Sandia Cable	Yes
3			1347:22	Roos type to Current Sensor	Yes
4	82231	Aug. 19	1315:20	Ruggerei GW to Current Sensor & Sandia Electronics	Yes

Note 1: All French firings with Ruggerei type 614 rockets
Note 2: Tipsy denotes ungrounded wire with Kevlar filament tie to earth.

TABLE 2

DATA ON TRIGGERED DISCHARGES TO AIR FORCE CYLINDER

1982 Date	Year/Julian Date	MST	French Firing Number	Peak Current (kA)	Duration (m s)
Aug 3	82215	1230:17	8209	9.3	441
Aug 5	82217	1630:36	8210	47	735
Aug 14	82228	1815:00	8224	30.4	140



site. The Air Force data were transmitted by a fiber optic link into a nearby metal trailer where they were recorded.

The French made direct measurements of the electric current carried by lightning with a 5 milliohm, Inconel resistor located beneath the Air Force test device and in the lightning path to earth.

The New Mexico Tech group used a similar resistor in one of its lightning triggers to an underground, electromagnetically shielded room (Kiva 2) on top of South Baldy Peak. In addition three, time derivative components [dB_n/dt, dB_E/dt and dD_z/dt] of incident electromagnetic fields were recorded in Kiva 1, another underground and shielded room on South Baldy Peak about 50 m south of Kiva 2. Electromagnetic waves incident at the site were detected by two orthogonal magnetic field sensors and one perpendicular displacement current sensor at ground level on the roof of Kiva 1. The magnetic sensors were Air Force MGL-3 B-dot instruments and an ACD-5 D-dot device was used to sense dD/dt. These component signals were recorded within Kiva 1 with the use of three Biomation 8100 waveform analyzers controlled by a Hewlett Packard 9825 computer. The waveform analyzers digitized any signals above trigger level sequentially with a 10 ns resolution and provided a 20 microsecond window for each data grab during a flash. About 25 ms was required for each data set after which the Biomation units were rearmed to await another signal above its threshold. Two data grabs were obtained with this equipment for several of these discharges.

Also recorded in Kiva 1 on analog magnetic tape were electric field strength, electric field changes, corona current thunder and a trigger mark indicating where in the flash that the waveform analyzers were triggered to start a data grab. Similar data were recorded at Langmuir Laboratory from a net of instruments deployed over an 1600 m span along the crest of the Magdalena mountain ridge. These included thunder signals from two equilateral triangular arrays of microphones. From these, the time difference of arrival of acoustic signals from thunder was used to reconstruct the locations of thunder sources along the lightning channels.

Video cameras and recorders were used both at Kiva 1 and at Langmuir Laboratory for motion photography of the triggered lightning with 30 ms resolution on video tape.

<u>Radar</u>

An 11 cm wavelength radar in development at Langmuir Laboratory was fitted with a radar signal processor and a digital recorder under this program for the study of lightning and its effects on clouds. Difficulties were experienced with the radar transmitter and the receiver in this period so that useable data were not obtained with it during the 1982 thunderstorm season. Since then we have continued with the radar modification and development and, at the end of the 1984 summer, we finally have the radar at the level where we can take data with it.

In its present configuration, a low-noise, travelling wave tube amplifier is incorporated in the front end of the radar receiver, followed by a logarithmic video amplifier for digital

data reproduction and by a linear video amplifier with gain wobble for photographic reproduction of the reflected radar signal. The pertinent parameters are:

minimum detectable signal	96 dBm
parabolic antenna	3.05 m diameter
beam width	2.5°
scan rate in vertical plane	10 rpm (24 beam widths/sec)
peak transmitted power	200 kW
pulse length	0.8 microsecond
pulse repetition rate	1 kHz
transmitting frequency	2808 MHz

Motion control of the antenna is programmed. In the scanning mode, the antenna sector scans in a vertical plane to each side of a preselected azimuth in two steps (beam widths) about the center sector. In fixed mode, the antenna points to a preselected direction. Azimuth and elevation data from syncro-to-digital converters are recorded on magnetic tape along with the radar reflectivity data. A view of the radar antenna is shown in Figure 3.

Cloud reflectivity is recorded photographically from horizon-to-horizon while the antenna is in the scanning mode and provides for visual examination of cloud motion through the radar beam. The linear dynamic range of the reproduced data is extended to about 36 dB by a 20 dB change in gain when the antenna is below the horizon.

Analog reproduction of the logarithmically-compressed, reflectivity data is accomplished with a video tape recorder. This provides for a A-scope examination of the data for lightning events which can then be used to identify time of occurrence of lightning in the digital data without extensive computer processing. The analog video tape carries IRIG B time code on the audio track. High and low reference signals, azimuth, and elevation codes are formatted on the video track along with radar trigger and the reflectivity signal. This allows computer processing of the video signal and provides for independent analysis in the event of malfunction of the digital data recording system. Tape-to-disk transfer occurs at a sampling rate of 640 kHz. With the analog systems, thirty range gates are sampled for cloud echo reflectivity. The width of each gate in range is 240 m so that the sampling interval is over 9.6 km in range. The starting point for the initial gate is selectable from 1.2 km to 7.2 km.

The digital data recording system digitizes the reflectivity information in real time at a 500 kHz rate. Digitizing is

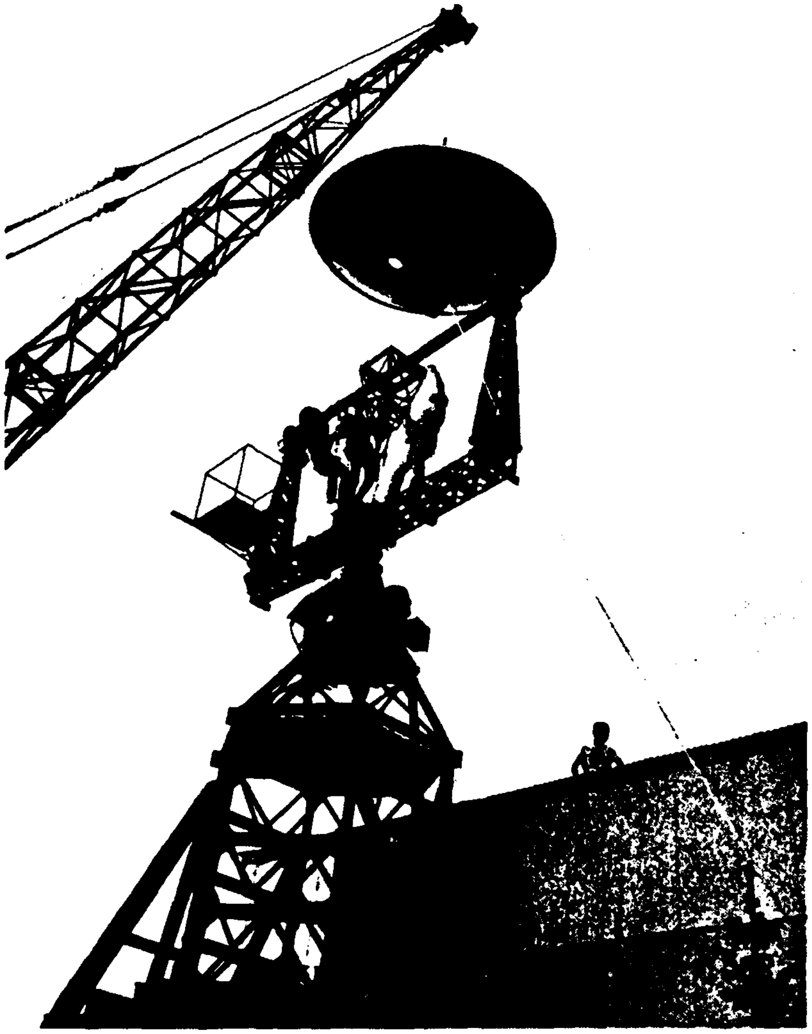


Figure 3. The antenna for the 11 cm radar developed to study the interaction between lightning and cloud particle growth. The reflector is a 3 m diameter paraboloid and the pedestal has been adapted from an FPS-6 aircraft height finding radar.

synchronized at an effective PRF of 500 sec^{-1} to the digital tape recorder and is initiated by the radar trigger. Forty range gates are sampled with a gate separation of 300 m in slant range with the first range gate at 1500 m. Whole sky coverage in range is accomplished by 'gate staggering' i.e. by delaying the initiation of gate sampling by 1 msec on alternate scans. Record length is 0.5 sec with the radar in scan mode four records are taken from horizon to 30^{o} past zenith. In point mode records are taken continuously for the duration of a tape, about 20 minutes.

Data processing is done 'after the fact' on the Langmuir Laboratory computer either as line plots for lightning events recorded under point mode operation or optionally as 16 false color, RHI reproductions for the reflectivity measurements taken in the scanning mode. This radar has been described in a thesis by Atchley(1982).

Lightning Data

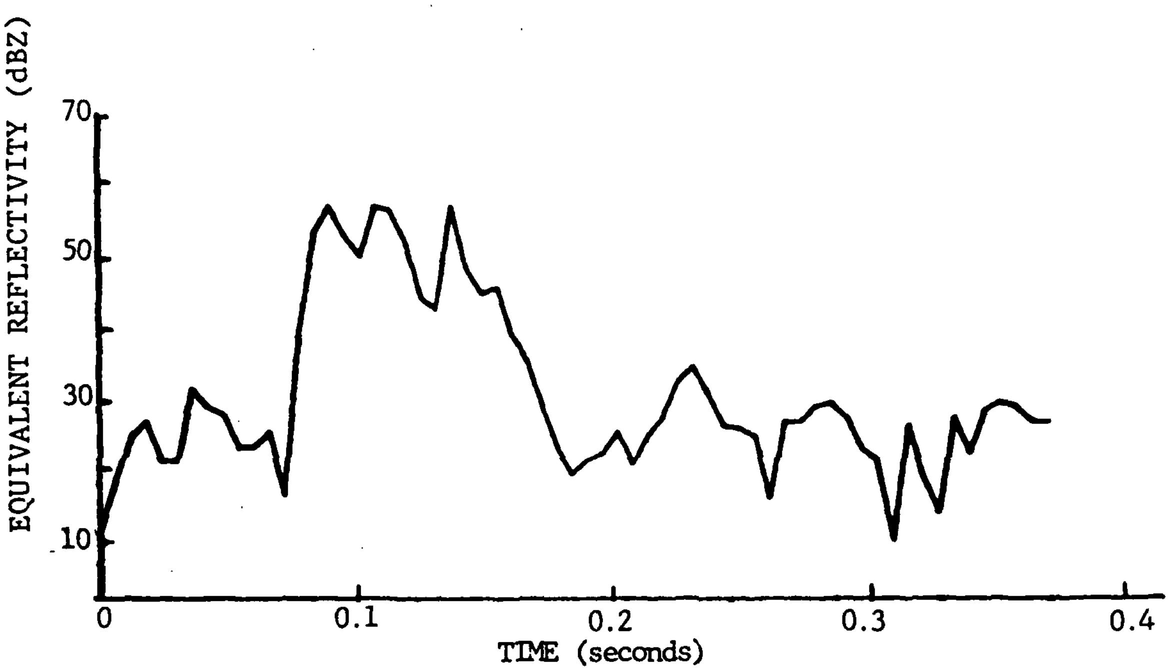
Plots of the lightning data recorded for the three strikes are given in Appendix 2. Analysis of these data indicate electromagnetic signals with time derivative strength in excess of 10 Teslas/sec at the 350 m range of Kiva 1. The rise times of these pulses varied from 40 to 80 ns for leaderlike pulses and 300 to 1000 ns for the return strokes in the discharges. From these data we estimated the magnitudes of the electrical currents using the technique described by Baum et al.(1982). Our estimates of the peak currents range from 0.1 to 3 kA for the leader pulses and 3 to 40 kA for the return strokes.

We were able to measure the peak lightning current directly through the 5 milliohm Inconel resistor on Kiva 2 for the discharge triggered there on August 19, 1982. A value of 79 kA was recorded for this discharge but no waveform data for comparison were captured for this flash. An example of a lightning echo to the 11 cm radar is shown in Figure 4 for a fixed gate set for a range of 5 km for measurements during the 1983 season. Initially an echo due to precipitation in the beam dominated the return but about 75 msec after the start of the record, the echo intensified a thousand fold but somewhat slowly from about 27 dBZ ($Z = 500\ mm^6/m^3$) to an equivalent of about 57 dBZ ($Z = 500{,}000\ mm^6/m^3$) then, after 0.1 sec, decayed with a time constant of about 4 ms. Presumably the relative slow intensification indicates lightning propagation across the beam while the decay time constant is a measure of recombination after cessation of current flow. We expect to obtain and analyze more data of this type now that the radar has been completed.

ANALYSIS OF THE CONDITIONS REQUIRED FOR THE INITIATION OF LIGHTNING

One purpose of our study has been to make measurements of the breakdown field and of the relaxation times involved in the propagation of positive streamers emitted from elevated wires.

An analysis of the atmospheric electric fields and potentials involved can be made using the surface electric field measurements



YEAR: 1983 DAY : 83223 TIME: 1127:887 MST

AZIMUTH: 2 ELEVATION: 21.3

POWER: 225 START SCAN: 750

AVERAGE: 2 SCANS SCANS PLOTTED: 250

Figure 4. Plot of the echo power returned to the 11 cm radar from a lightning channel studied on Aug. 11, 1983. The echo power is given in terms of the equivalent cloud echo reflectivity with units of dBZ (10 log Z where Z has units of mm^6/m^3)

with Gauss' and Ohm's laws. The one dimensional divergence of the electric field in the vertical direction is given by

$$dE_z/dz = \rho/\varepsilon$$

where ρ is the space charge density and ε the atmospheric permittivity. From Ohm's law, the density, j, of the electric current flowing in a medium of conductivity λ under the influence of an electric field is given by

$$j = \lambda E.$$

Now λ can be defined by ρK where K is the ionic mobility. Accordingly,

$$E_z \, dE_z/dz = j/\varepsilon K.$$

When this relation for E_z is integrated over a height interval h with a constant current density,

$$E_z(h) = \{E(0)^2 + 2jh/\varepsilon K\}^{1/2}.$$

In the absence of significant current carried by rain, the current density, j, can be estimated by determination of the displacement current density, $\varepsilon dE/dt(E = 0)$, during the field recovery after a lightning discharge. When the field strength crosses zero and then, momentarily, all field-dependent currents are equal to zero, the total current density is carried by the displacement current which can be determined from the slope of the recovering field strength.

With a continuation of this approach, the potentials at various levels in the atmosphere relative to the earth may be inferred by integrating $-E_z dz$ over the altitude intervals of interest:

$$\phi(h) = \{K/3j\}\{E(0)^2 + 2jh/\varepsilon K\}^{3/2}.$$

A listing of the electric fields and wire heights is given in Table 3 for the 1982 lightning triggerings for which there are useable data. From this analysis it appears that to trigger positive streamers, the wire must cut across atmospheric potential differences of greater than 3 MV at speeds greater than the drift velocity of point discharge ions (about 100 m/sec.) The inferred undisturbed field strengths at the level of the rocket must also be greater than 35 kV/m.

TABLE 3

ELECTRIC FIELD DATA ASSOCIATED WITH 1982 TRIGGERED LIGHTNING FLASHES

Julian Date	Time	E(o) kV/m	dE/dt (E=o) V/ms	j (nA/m)	h (m)	E(h) (kV/m)	V(h) (MV/m)
82210	1322:46	7.2	0.46	4.1	275	35	6.59
82212	101?:43	7.2	No z crossing		?		
	1024:21	13.5	No z crossing		?		
82215	1230:17	8.0	1.01	8.9	496	69	23.17
82217	1630:36	7.6	0.86		?		
	1632:03	7.6	0.35		?		
	1743:56	8.0	0.40		?		
82219	1151:35	6.6	0.55		?		
	1154:59	6.6	0.68		?		
	1202:30	7.8	0.51		?		
	1756:41	8.5	0.70		?		
82224	1614:44	6.6	0.24		?		
82228	1730	8.4	0.90		?		
	1815	9.8	0.76		?		
82230	1341:16	15.8	1.68	14.9	223	56	8.56
	1347:22	14.0			218		
82231	1315:20	18.9	1.54	18.6	112	37	3.14

? indicates that the height of the rocket at time of lightning-triggering was not determined.

THE PROPAGATION OF LIGHTNING STREAMERS

After a plasma is formed in the atmosphere, it can propagate as a streamer whenever the energy released by the exclusion of the local electric field by conduction processes ahead of the streamer exceeds that required to ionize the air sufficiently to exclude the field. The time, τ, required to reduce the electric field strength by e fold is given by

$$\tau = \varepsilon/\lambda \tag{1}$$

where λ is the electrical conductivity and ε is the permittivity of the air. The conductivity,

$$\lambda = \sum_i n_i q K_i \tag{2}$$

where n_i equals the concentration of i^{th} charge carrier, K_i is its mobility and q is the magnitude of the electronic charge. The charge carriers of interest here are electrons, so that the effective conductivity,

$$\lambda_e = n_e q K_e \tag{3}$$

where the subscript e denotes an electron.

The mean energy required to produce an ion pair is of the order of 34 eV (5.4×10^{-18} J) whereas, the energy density in the electric field, E, is given by $0.5\ \varepsilon E^2$. We can estimate, therefore, the field relaxation times necessary for field exclusion by equating the energy density required for ionization to that given up by excluding the critical electric field, E_c:

$$0.5 \varepsilon E_o^2 \geqslant 34 q n_e . \tag{4}$$

Since $n_e = \varepsilon / q K_e \tau$,

Equation (4) becomes $E_c^2 \geqslant 68/K_e \tau$

and

$$\tau \geqslant 68/E_c^2 K_e . \tag{5}$$

Positively-charged streamers of plasma propagate in weaker electric fields than do negatively charged ones. For this reason, and also because negative charges predominate in the lower regions of thunderclouds, positively charged streamers are more likely to be launched upward from a grounded object than are negative ones.

A positive streamer propagates as a result of photo-ionization processes. Ultra-violet photons, emitted near the tip of a positive streamer, ionize air molecules ahead of the streamer. Electrons liberated in this manner are attracted to the positive tip and acquire significant kinetic energies as they fall through the strong electric field. On collision and/or recombination with positive ions at the streamer, they cause the emission of new uv photons that continue the process and thus, the streamer with its residual positive charges is elongated.

The critical strength of the electric field above which positive streamers can propagate has been found [by Phelps (1971) and others] to be about 4×10^5 V/m (at sea level pressure); this value varies directly with the atmospheric pressure so that, at the level of South Baldy Peak, electric field strengths in excess of 3×10^5 V/m are probably required for the upward propagation of a positive streamer. Since electronic mobilities, under these conditions may be of the order of 0.5 m^2/Vs, field strength relaxation times of about 1 n sec may be the lower bound for positive streamer propagations. From the preceding discussion, we might expect that the characteristic time for the streamer to propagate onward by one step is similarily defined.

Another way to treat Equation (5) is to write

$$\bar{E} K_e \tau = \bar{\ell} \simeq 68/E_c \qquad (6)$$

where $\bar{\ell}$ is the mean distance that would be travelled by an electron migrating inward under the mean influence of E during the relaxation time. Since the mean strength of the field acting on an electron moving toward the conductive core of an advancing streamer probably lies between that of the ambient (critical) field and that at the streamer tip,

$$68/\bar{E} \geqslant \bar{\ell} \qquad (7)$$

For $\quad \bar{E} \geqslant 3 \times 10^5 V/m, \quad 0.2mm \geqslant \bar{\ell}. \qquad (8)$

The mean electron velocity in this model would be about 10^5 m/sec which is the same order as the propagation velocity observed for positive streamers and that suggests that these estimates are of the proper order of magnitude.

These inferences are further supported by the work of Shlanta (1972) who estimated the mean free path lengths for photons produced by point discharges into air at a pressure of 695 mb (that of Langmuir Laboratory). He concluded, that in the mid region of the Shummann Runge absorption region at a wave length of about 1400 Å , the photon mean free path length was of the order

of 0.14 mm, about the same as our inferred propagation step.

From the preceding considerations, it would appear that, if we wish to make electrical waveform measurements on the breakdown processes, we will need time resolutions of about 1 ns.

This work led us to inquire about the strength of the initiating currents associated with the initial breakdown processes. These currents are in the milliampere range, well below the resolution of either the Inconel shunts or the waveform analysis techniques. A protected operational amplifier sensor to measure the initial currents in a discharge serially with the less sensitive ammeter was developed in the later extension of this program. This device in its final form has not yet been tested on a triggered discharge but we hope to obtain data with it next summer.

SUMMARY

Lightning discharges were initiated on 17 occasions in 1982 in a cooperative experiment carried out by investigators from the French Commissariat a l Energie Atomique, the U. S. Air Force Wright Patterson's Flight Hazards Branch and personnel from the New Mexico Institute of Mining and Technology. Electrical current and waveform measurements were obtained on these discharges. The currents experienced ranged from a few hundred amperes to a peak indication of 79 kA.

The development of an 11 cm radar for the study of the interaction of lightning with the surrounding atmosphere was completed under this program and is being used in current studies.

The behaviour of rockets used in lightning triggering work was determined and a recipe for lightning initiation has been developed. Lightning can probably be triggered when negatively charged clouds are overhead producing surface field strengths in excess of 9 kVm by the rapid injection into the subcloud region of a grounded wire at vertical speeds in excess of 100 m/sec to heights in excess of 150 m.

Analyses indicate that lightning may be triggered more easily by these smaller rockets than have previously been used.

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Szymanski, E. W., S. J. Szymanski, C. R. Holmes, and C. B. Moore, "An Observation of a Precipitation Echo Intensification Associated with Lightning", J. Geophys. Res., 85, pp. 1951-1953, 1980.

APPENDICES

1. Reports prepared with support in part by AFOSR Grant 82-0206 (abstracts follow).
   Measurement Note 27: "Characteristics of French Ruggieri Antihail Rockets Used to Trigger Lightning" by C. B. Moore, I. J. Caylor, D. L. Hall and T. F. Stueber, Nov. 25, 1982.
   Measurement Note 29: "Characteristics of American Rockets Used for Triggering Lightning" by C. B. Moore, D. L. Hall, I. J. Caylor, T. F. Stueber, Bryan Cason and Duane Patrick, February, 1984.

2. Electric Field and Thunder Data for the 1982 French Rockets Triggering Lightning to the Air Force Test Cylinder

Measurement Notes

NOTE #27

November 25, 1982

CHARACTERISTICS OF THE FRENCH RUGGIERI ANTI-HAIL ROCKETS USED TO TRIGGER LIGHTNING

by
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and
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ABSTRACT

Lightning can be triggered by the rapid injection of a grounded wire into regions with strong electric fields beneath a negatively charged thundercloud if the upper tip of the wire moves faster than the drift velocities of corona ions emitted from the wire. Field strengths in excess of 9 kV/m, wire tip velocities in excess of 150 m/sec and wire tip heights in excess of 100 m are required for a high probability of triggering lightning over land.

Measurements of the performance of the French Ruggieri rockets used by Hubert et al. for triggering lightning indicate that these rockets provide impulses of about 640 N s, velocities of about 300 m/sec, peak accelerations of about 30 g with apogees of about 1800 m.

We conclude that lightning may be triggered by use of somewhat smaller rockets, under favorable conditions from mountain peaks.

Measurement Notes

Note 29

February 27, 1984

CHARACTERISTICS OF AMERICAN ROCKETS USED FOR TRIGGERING LIGHTNING

PART 1. ROCKETS FROM FLIGHT SYSTEMS INC., BURNS FLAT, OKLAHOMA

by

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ABSTRACT

The performance characteristics of small rockets - used for towing wires into regions with strong electric fields beneath thunderclouds - have been measured at Sandia National Laboratories. The thrust delivered by each type of rocket engine was determined by strain gages in static firings on the ground. Similar engines were fitted with nose cones and fins, then launched vertically. They were tracked by a distance-measuring, laser-theodolite that provided slant range, azimuth and elevation information from which location coordinates, vectorial velocities and accelerations were calculated.

Drag coefficients were estimated for these rockets using the position and velocity data after the end of thrust; the calculated coefficents ranged from about 0.8 to 1.1.

Other rockets of these types were used to deploy steel wires from bobbins. The data from these and the earlier tests were used to obtain estimates of the forces exerted on the rockets by the wire deployment and of the forces required to accelerate the wires.

The rocket engines used in these tests had thrusts measured between 47 and 200 N with impulses ranging from 123 to 207 Ns. The duration of thrust from these engines was from 1 to 3.5 sec. The forces exerted on the deployed wire often exceeded its 80 N breaking strength. A performance predictor program has been prepared from these studies to match the rocket engine performance with the requirements for optimum, high-speed wire deployment without breaking the conductor.

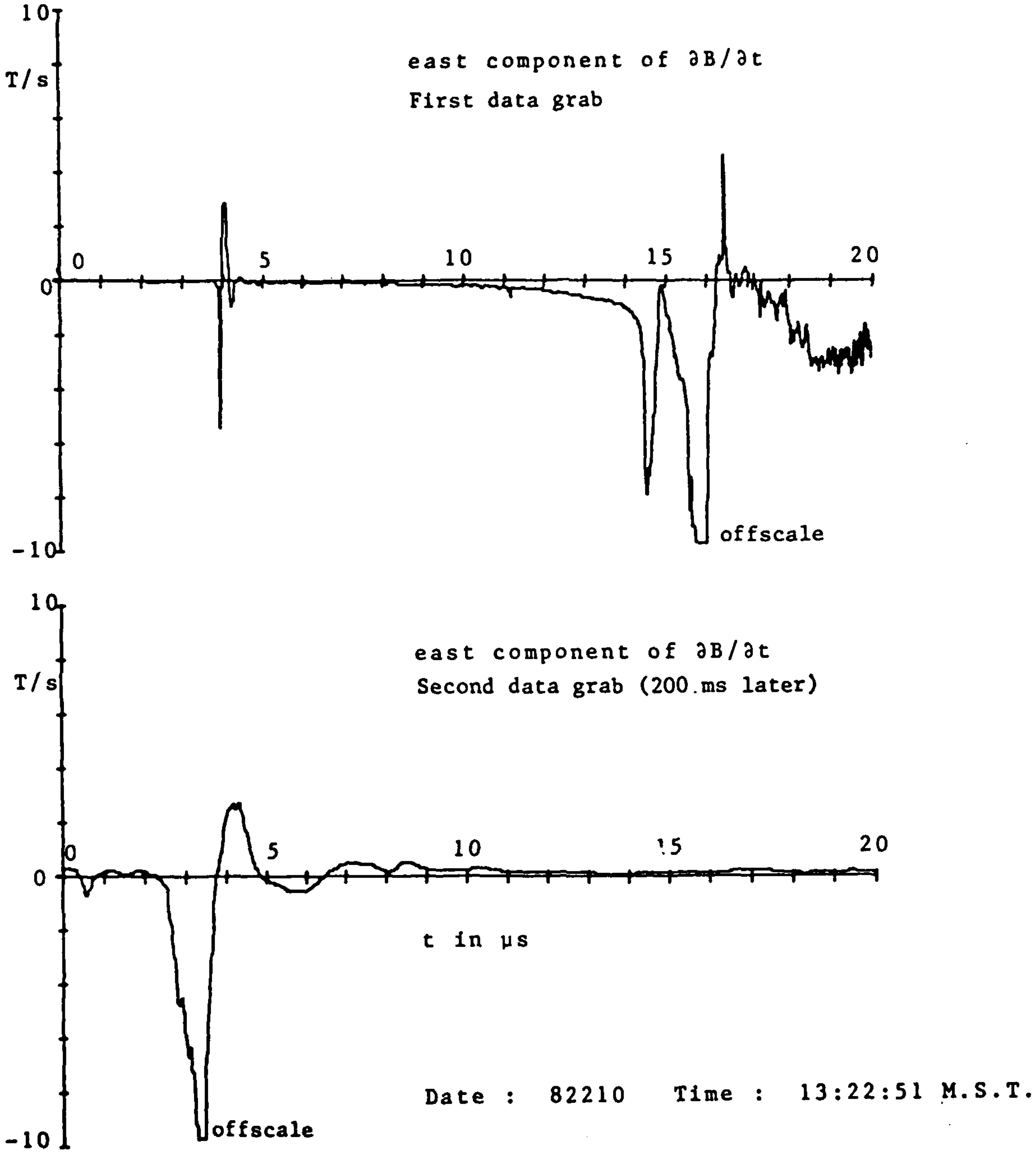

Figure A-1. Electromagnetic signals received at Kiva 1 from rocket-triggered lightning at a distance of 363 m on July 29, 1982 at 1322:51 MST.

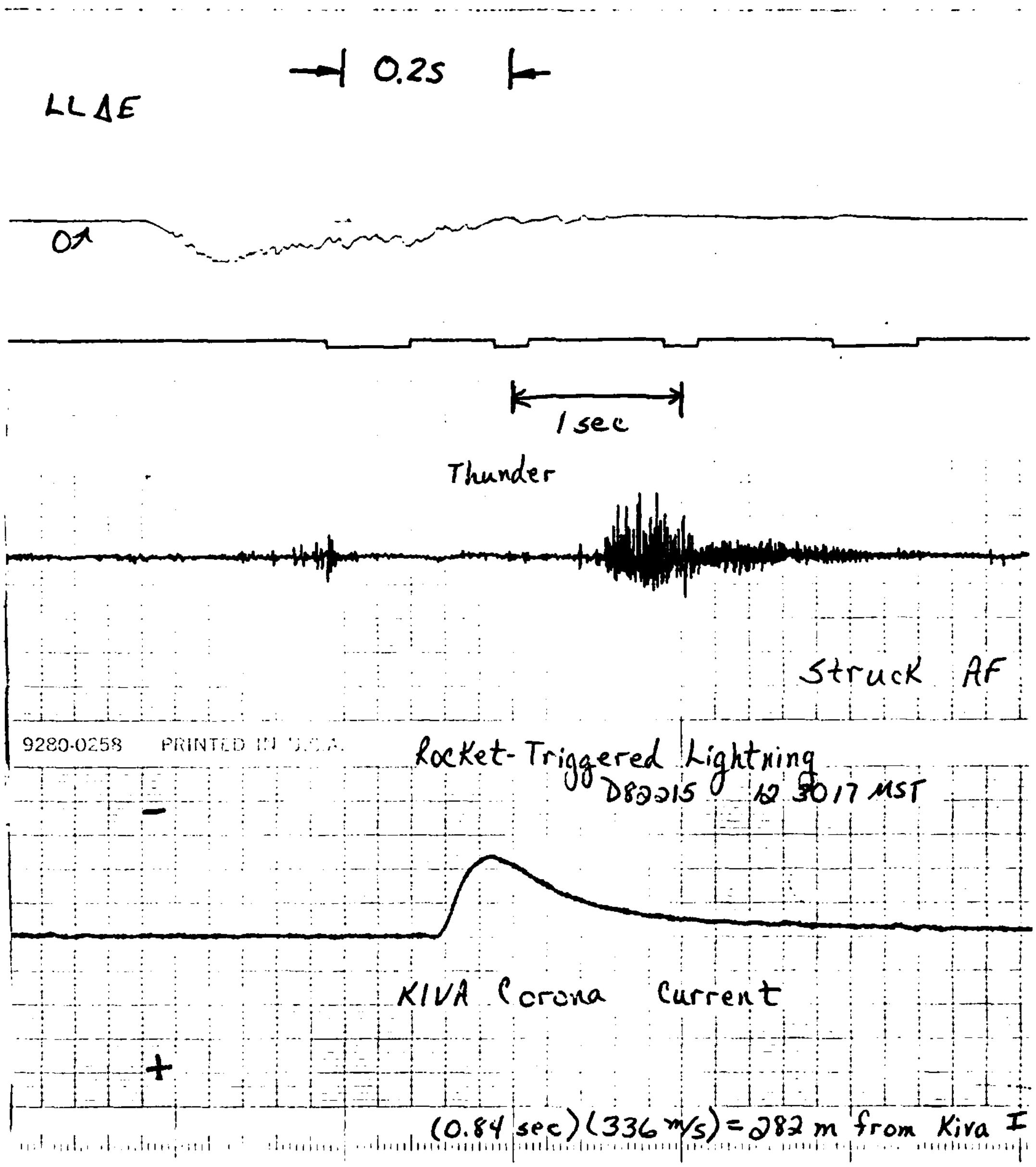

Figure A-2. Plots of the electric field change observed at Langmuir Laboratory (1650 m distant) and the thunder and corona current recorded at Kiva 1, 282 m from rocket-triggered lightning on August 3, 1982 at 1230:17 MST.

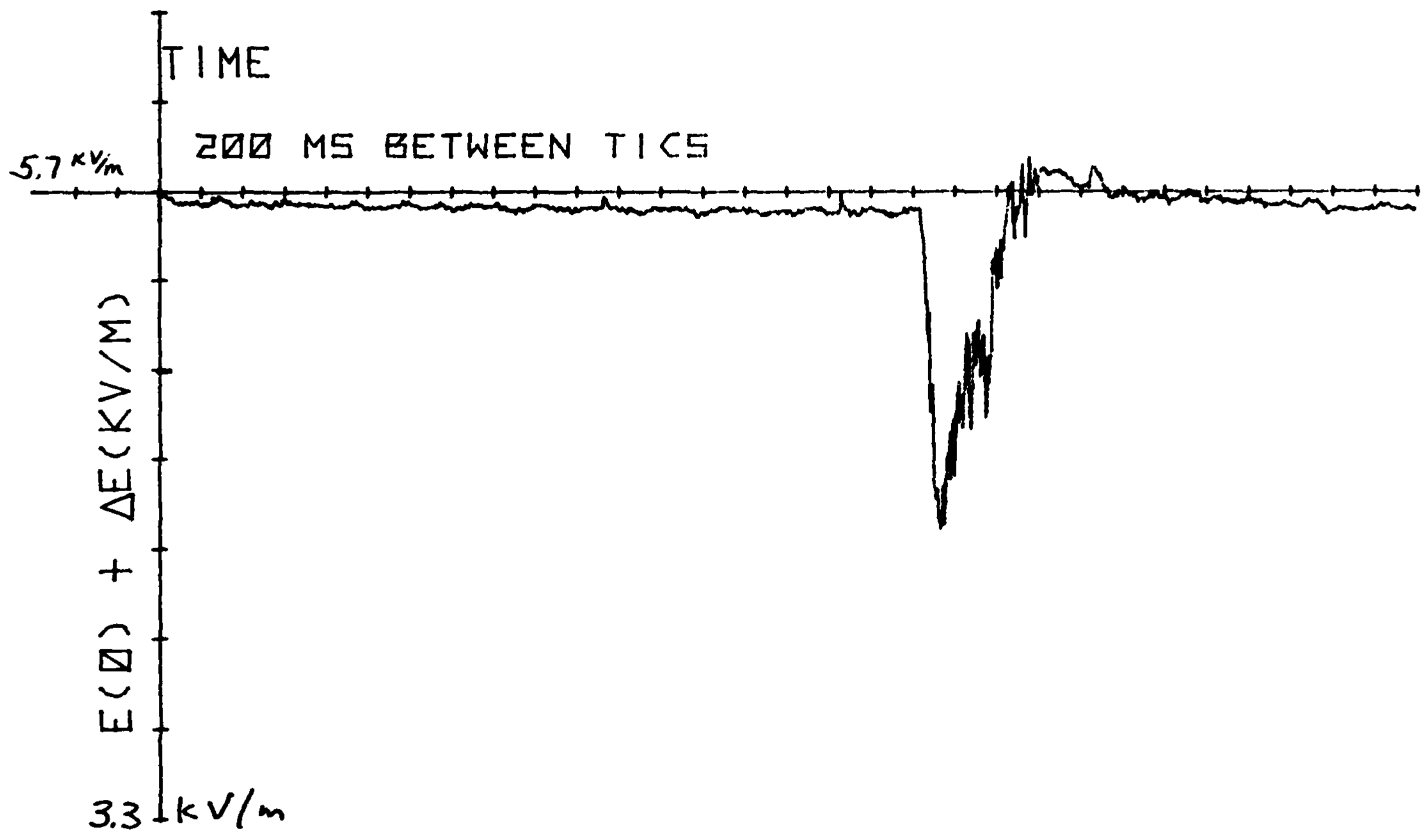

Figure A-3. Reconstructed electric field from the field change record received at Langmuir Laboratory from rocket-triggered lightning on August 3, 1982 at 1230:17 MST. This record depicts the field changes caused by positive charge along the triggered channel followed by a neutralization phase that often leaves the ambient field unchanged after the triggered discharge.

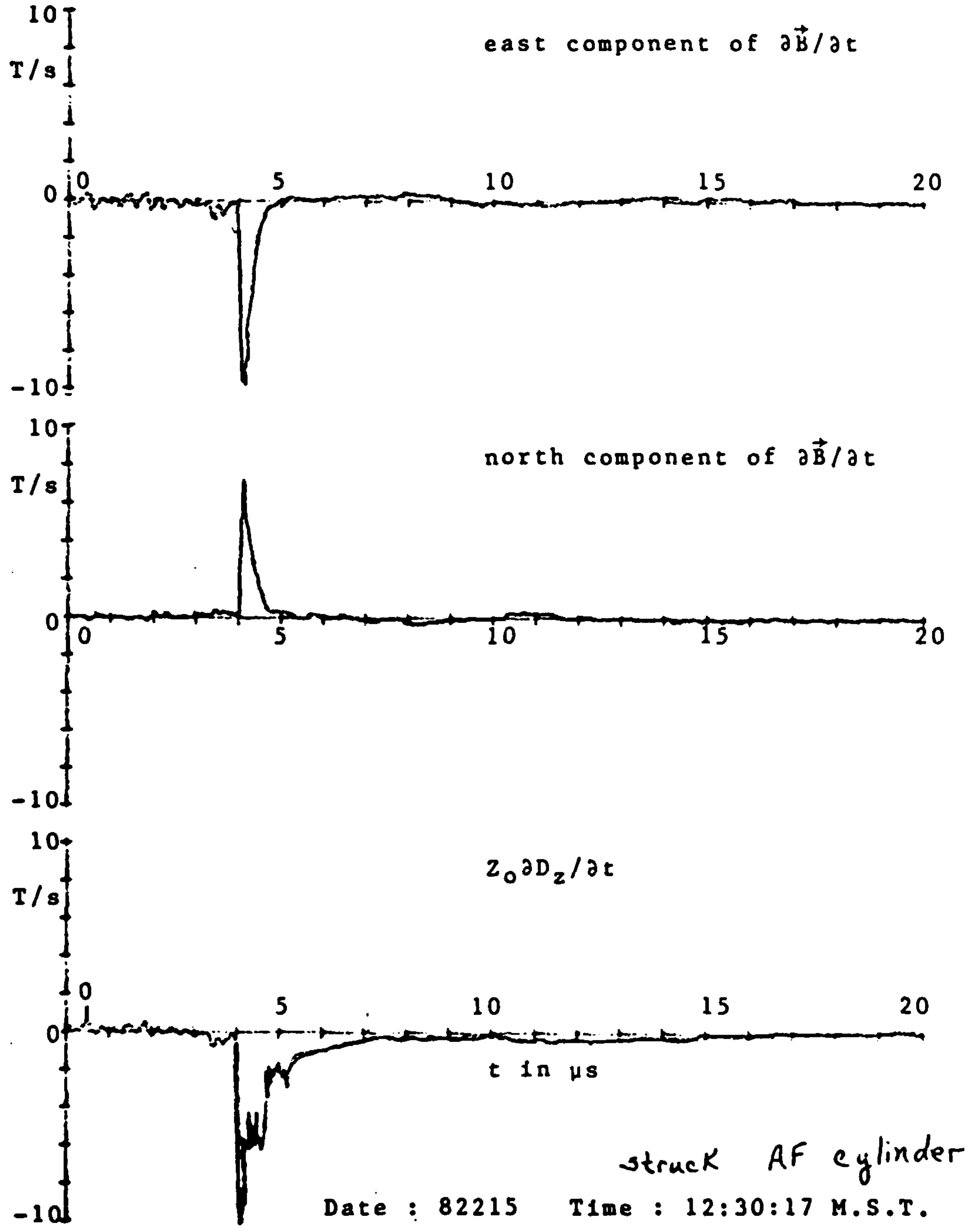

Figure A-4. Electromagnetic signals received at Kiva 1 from rocket-triggered lightning at a distance of 282 m on August 3, 1982 at 1230:17 MST.

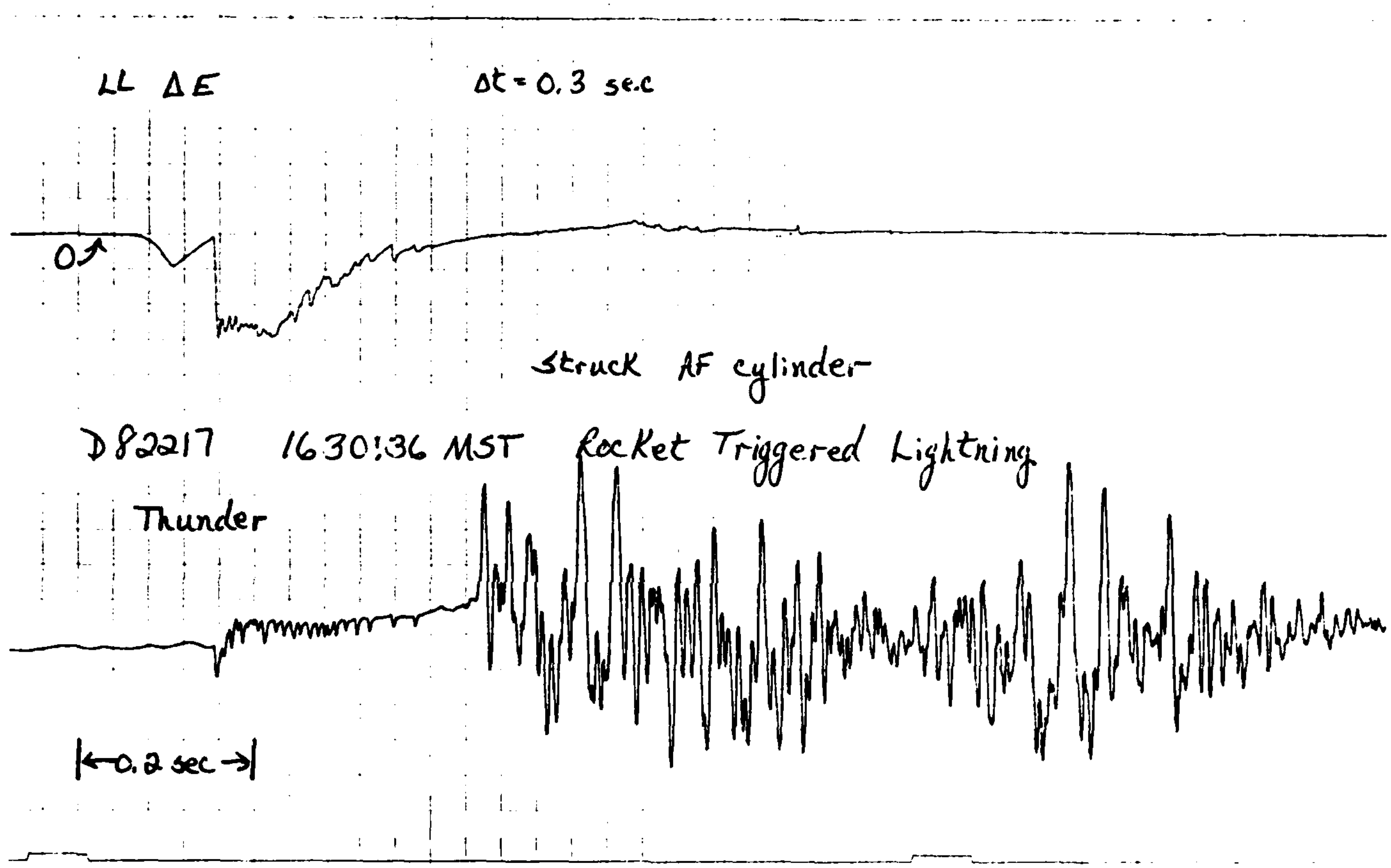

Figure A-5. Plots of the electric field change recorded at Langmuir Laboratory and the thunder recorded at Solar Tower for the rocket-triggered lightning on August 5, 1982 at 1630:36 MST. The early field change and the early noises are due to the rocket. There were 10 or more return strokes associated with this discharge after its initiation.

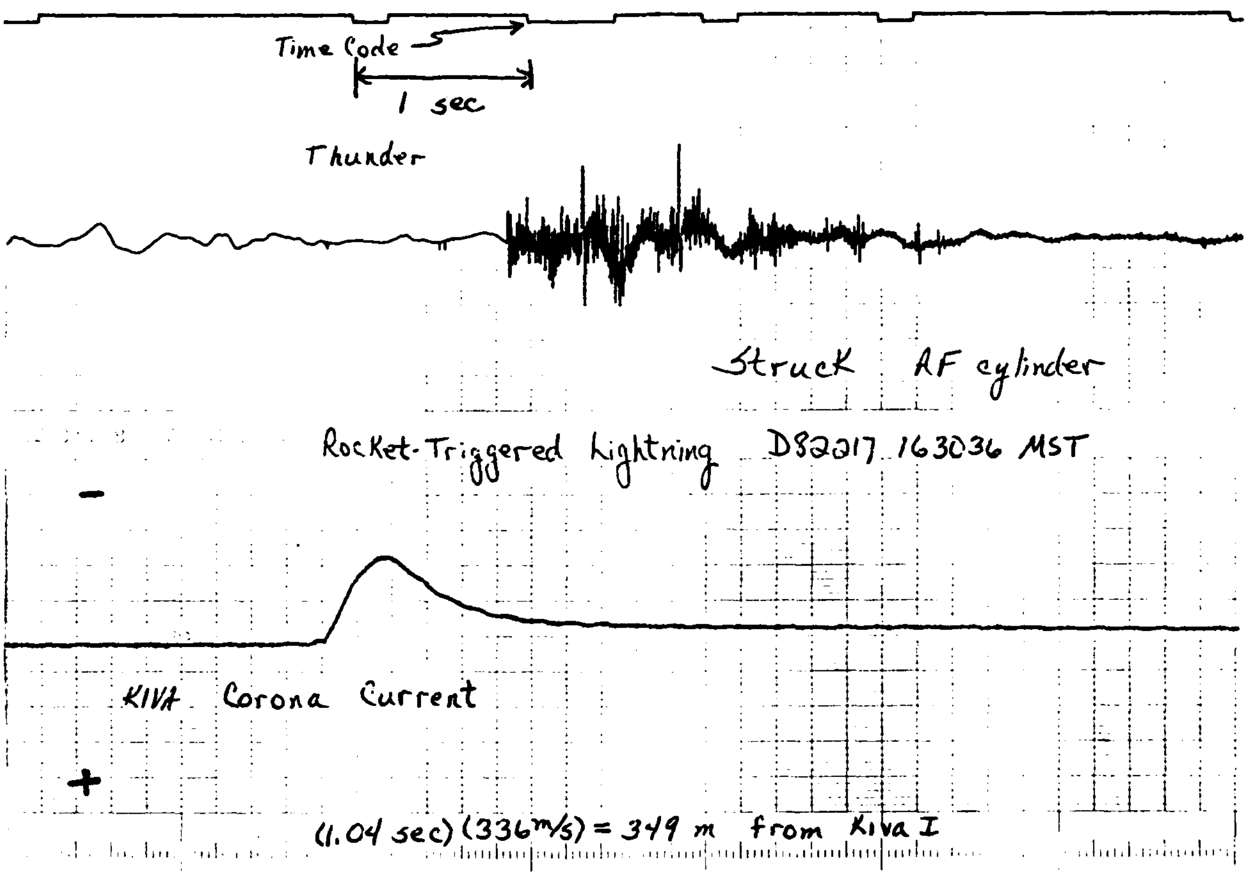

Figure A-6. Thunder and corona current at Kiva 1 following the triggered lightning 349 m distant in August 5, 1982 at 1630:36 MST. A large burst of negative charge flowed in to the air following the creation of a positive streamer overhead by the rocket.

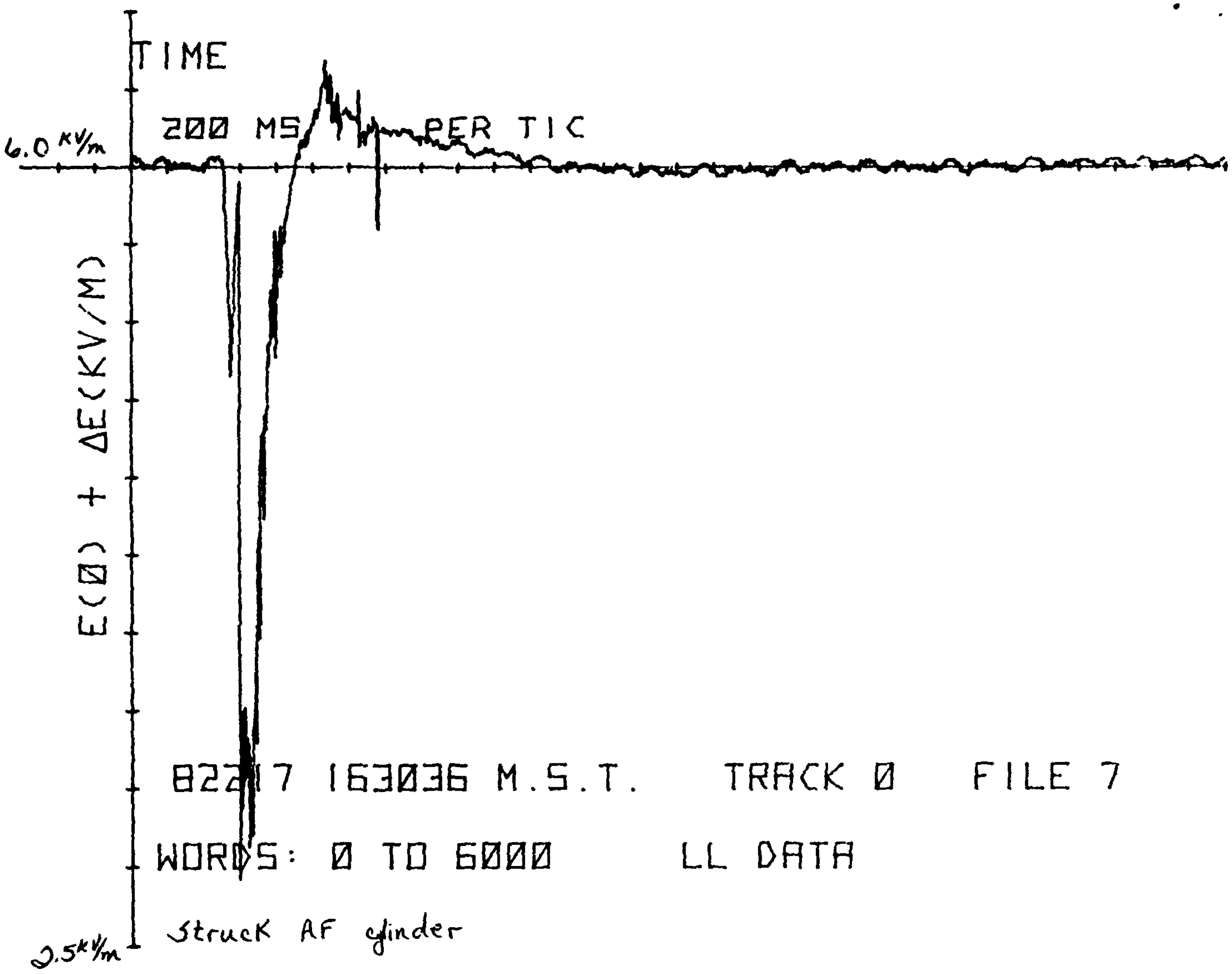

Figure A-7. Reconstructed electric field from the field change recorded at Langmuir Laboratory *from* rocket-triggered lightning on August 5, 1982 at 1630:36 MST. The electric field behaviour shown here is similar to that in Figure A-3.

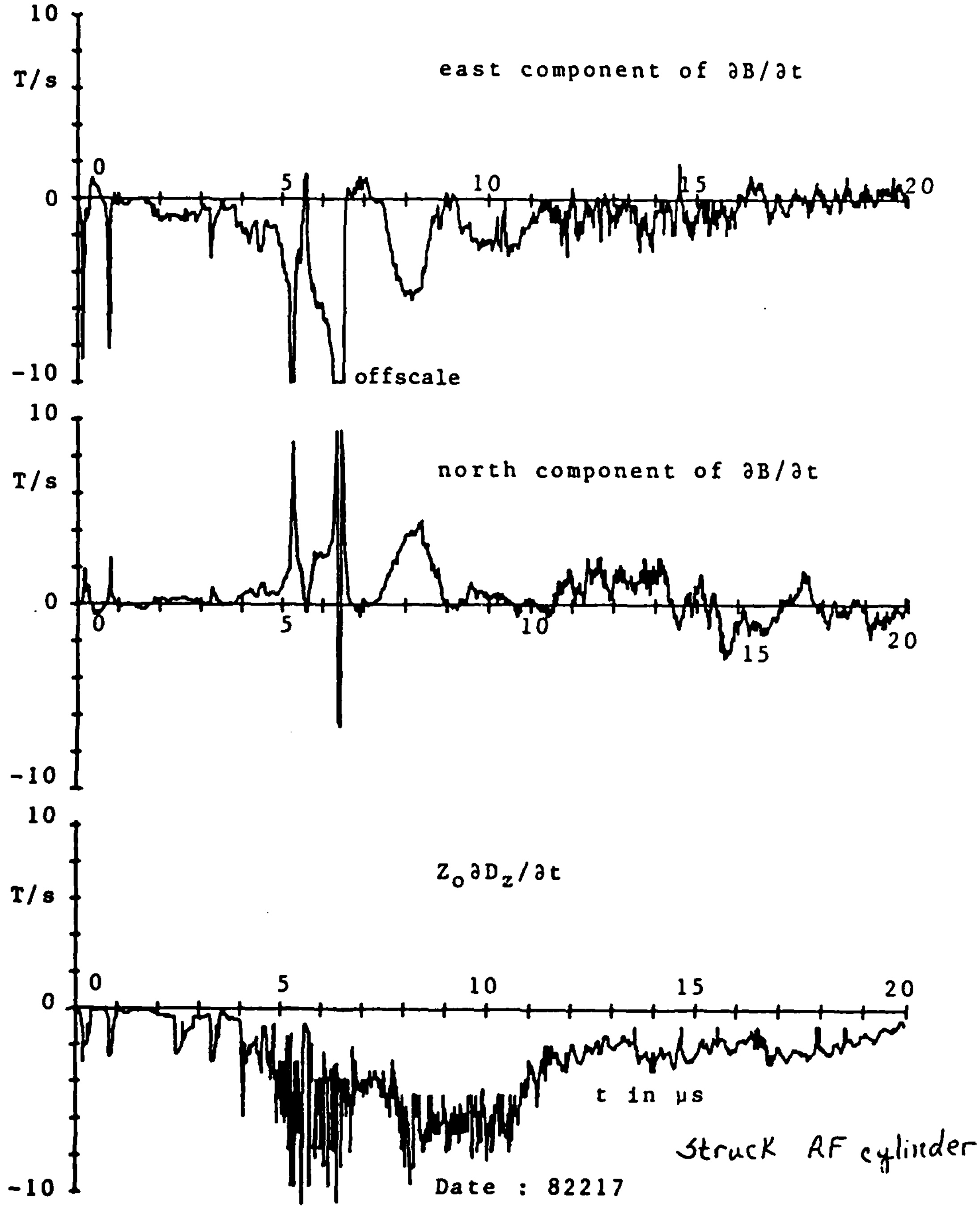

Figure A-8. Electromagnetic signals received at Kiva 1 from rocket-triggered lightning at a distance of 349 m on August 5, 1982 at 1630:36 MST.

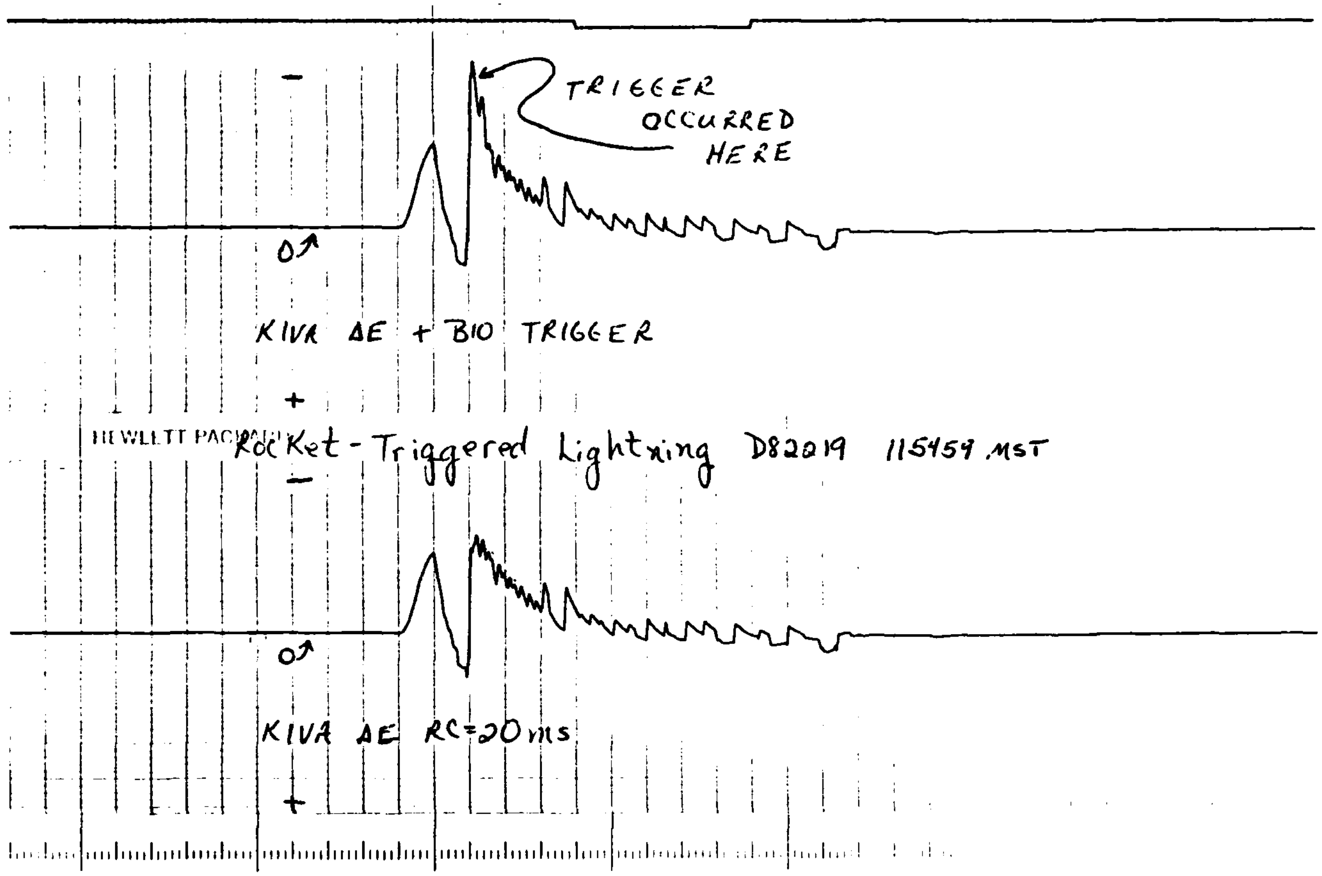

Figure A-9. Electric field changes recorded at Kiva 1 for the rocket-triggered lightning 309 m distant on August 7, 1982 at 1154:59 MST. More than 26 separate field changes associated with return strokes occurred in this discharge.

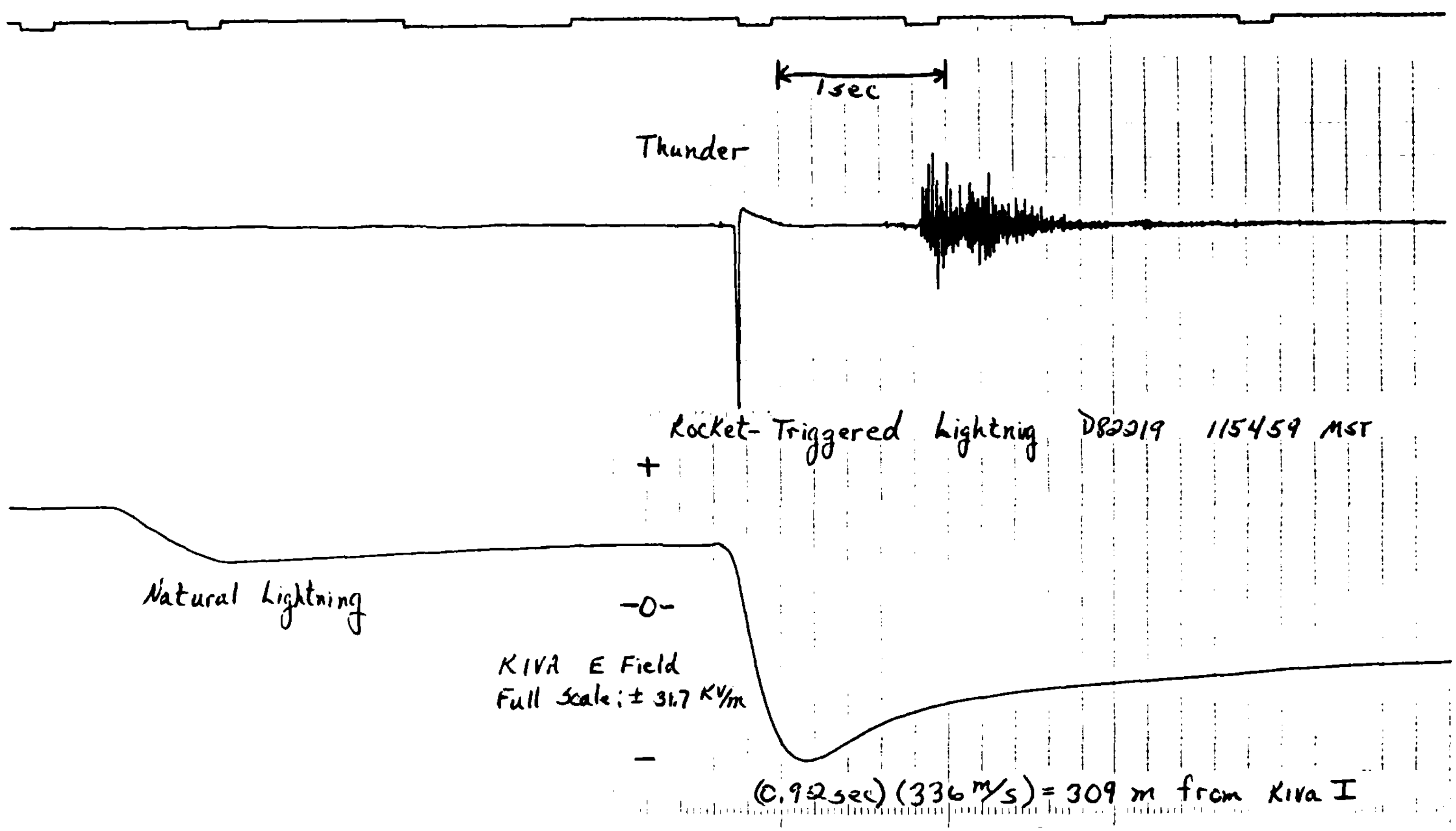

Figure A-10. Plots of the thunder and electric field recordings at Kiva 1 associated with the rocket-triggered lightning 309 m distant on August 7, 1982 at 1154:39 MST. After the discharge there was a region of positive charge remaining over the Kiva area.

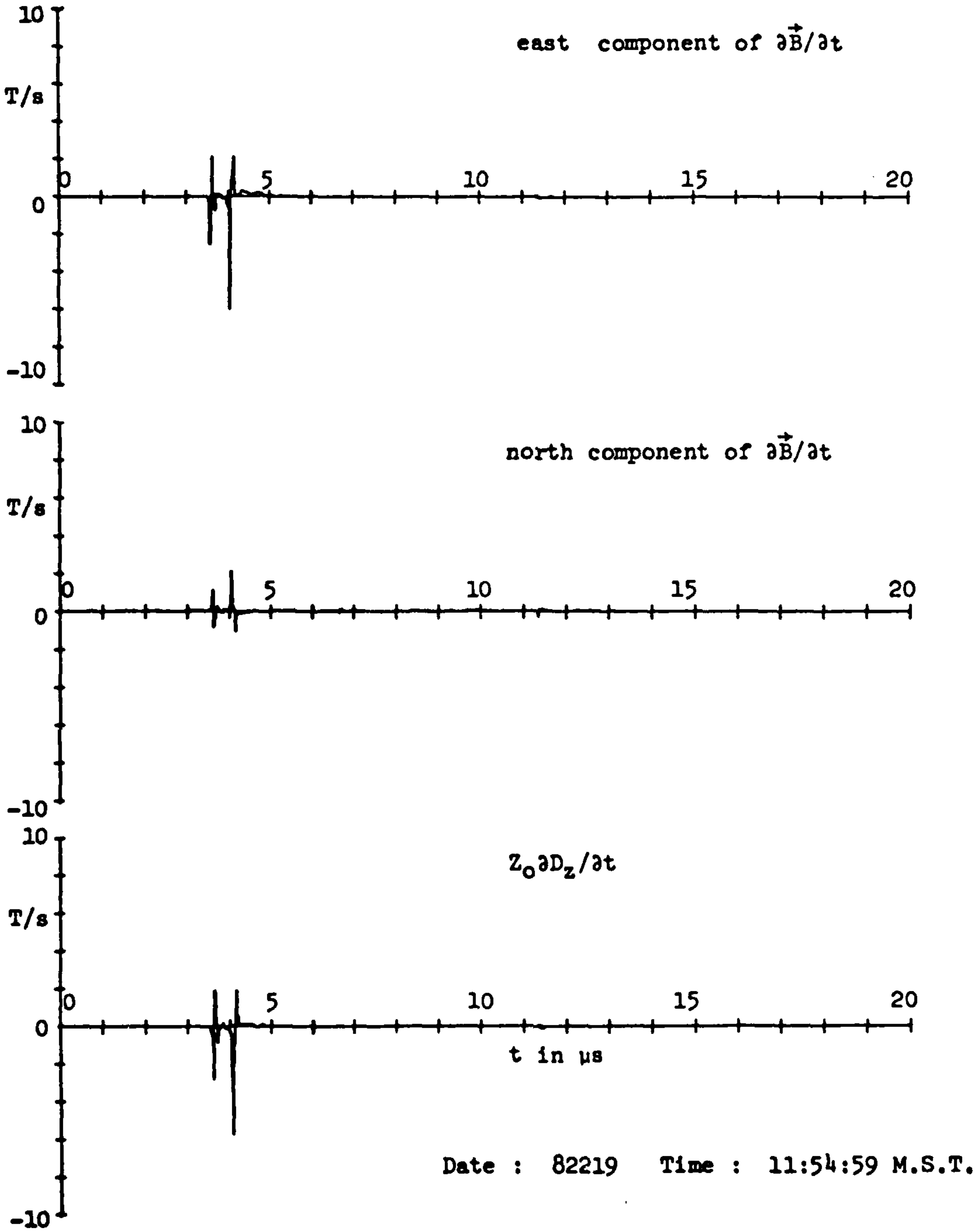

Figure A-11. Electromagnetic signals received at Kiva 1 from rocket-triggered lightning at a distance of 309 m on August 7, 1982 at 1154:59 MST. This record shows the typical signals associated with the leader streamers in the initial breakdown process.

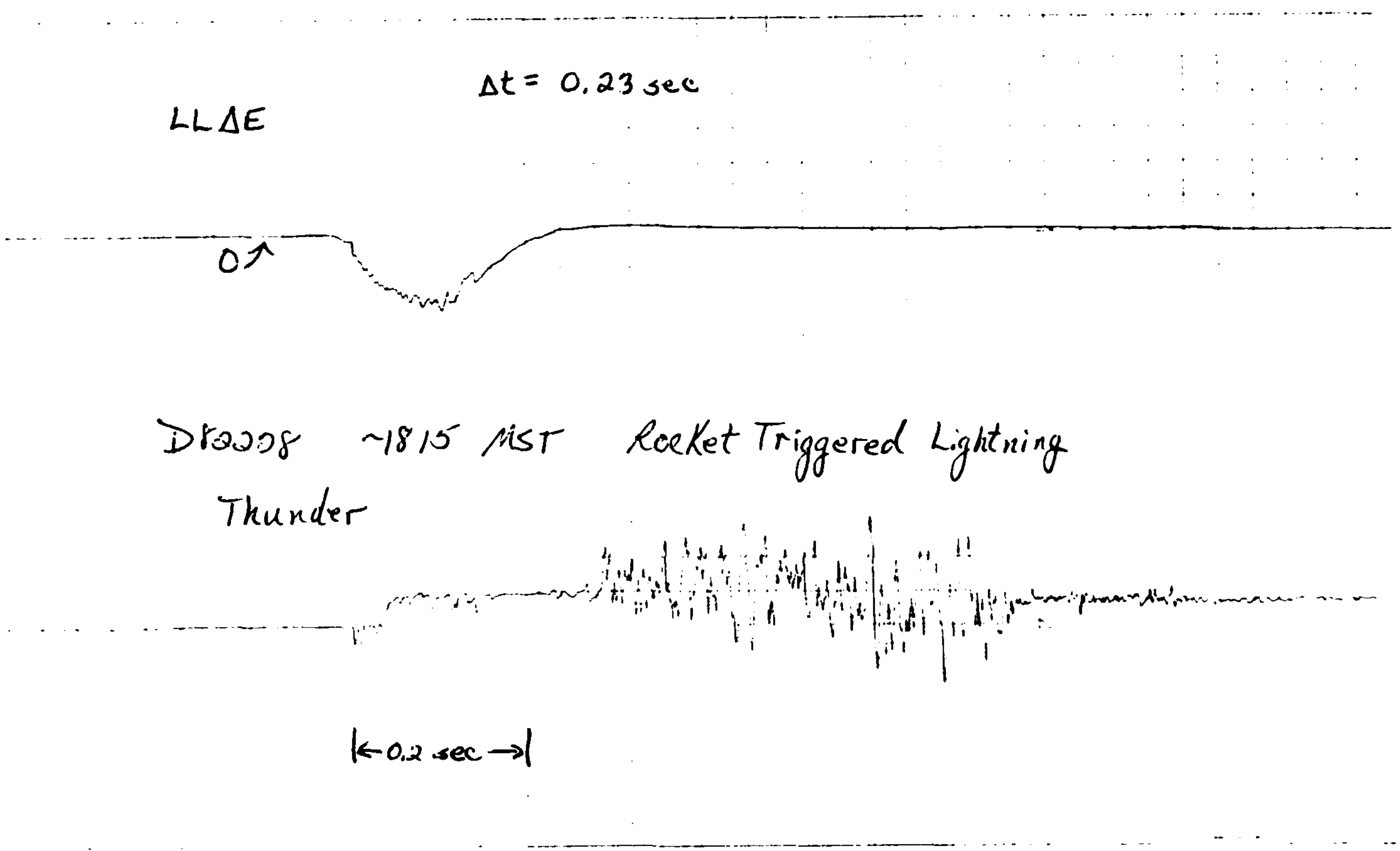

Figure A-12. Recordings of the electric field change at Langmuir Laboratory and the thunder received at Solar Tower from the rocket-triggered lightning on August 16, 1982 at 1815 MST.

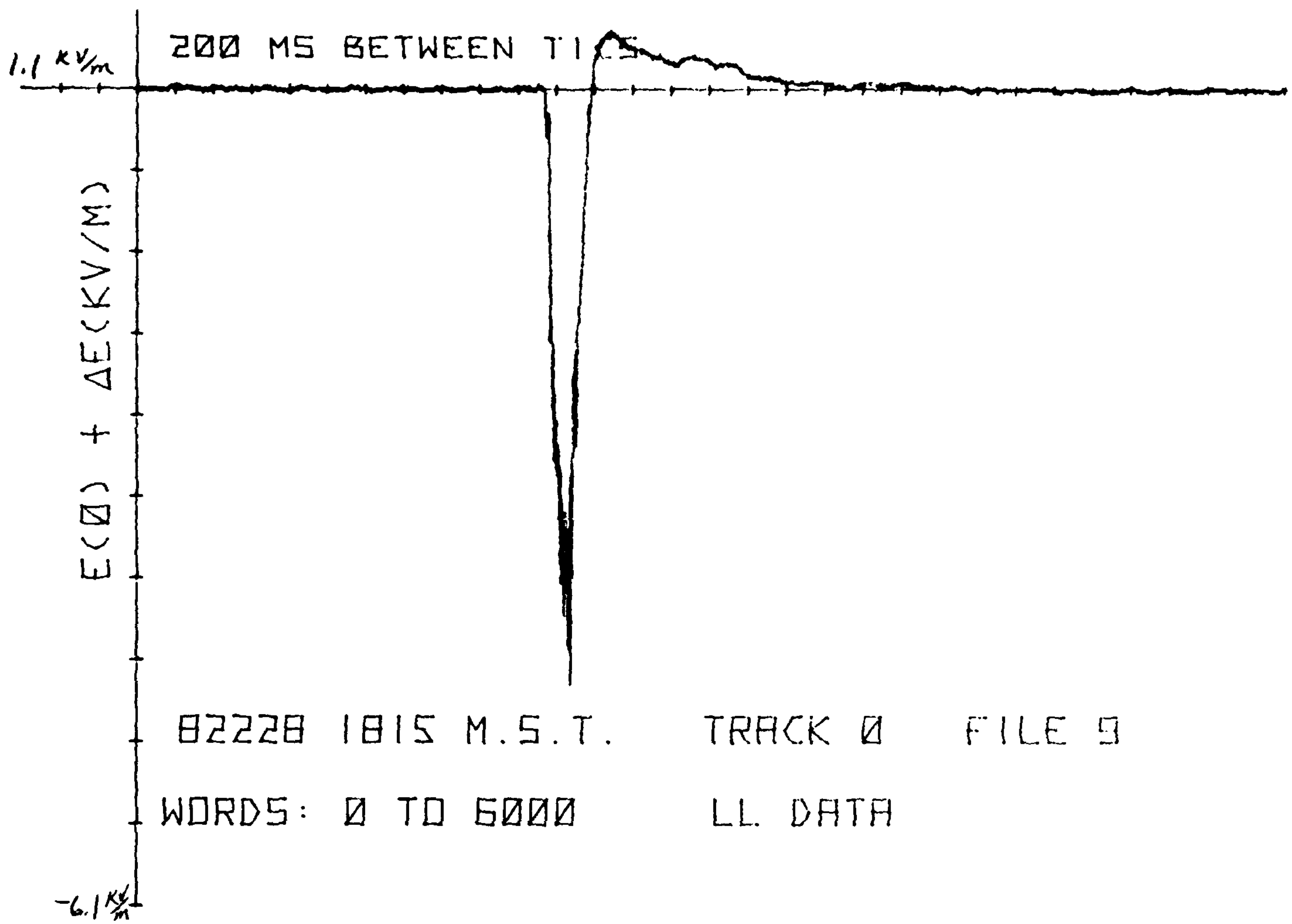

Figure A-13. Electric field reconstructed from the electric field change recorded at Langmuir Laboratory associated with the rocket-triggered lightning on August 16, 1982 at 1815 MST. This reconstruction again shows the limited effect of rocket-triggered lightning with the local deposition of positive change followed shortly by its removal.

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